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MEASUREMENT OF TURBULENT HF FIELDS IN A HIGH CURRENT RECTILINEAR GAS DISCHARGE FROM THE INTENSITY OF FORBIDDEN HeI LINES

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At the present time, there are very few experiments /203*
investigating a plasma which is free of any turbulence. Therefore, a study of the plasma turbulent condition may be of great importance both for plasma heating and for plasma confinement.

The energy level of plasma pulsations is one of the basic parameters for the plasma turbulent state. The short wavelength of turbulent pulsations in a plasma makes it impossible to analyze it by means of electrostatic probes. An ideal probe is an emitting atom whose dimensions are much less than the length of these pulsations. In 1961 Baranger and Mozer predicted the formation of satellites close to the helium forbidden lines, whose intensity must be proportional to the energy of the plasma pulsations [1]. The first such satellites were observed in a plasma of an induction discharge with no electrodes [2]. However, this study presented no additional data pointing to the excitation of plasma pulsations. The study discovered and investigated satellites close to the forbidden line of HeI in the case of turbulent plasma heating in a high current rectilinear gas discharge.

*Numbers in the margin indicate the pagination of the original foreign text.

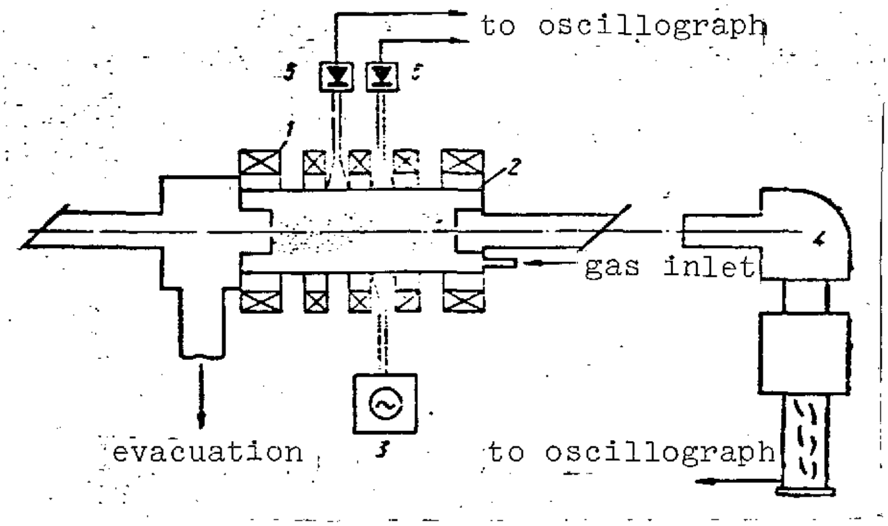

Figure 1. Diagram of equipment.

1- solenoid; 2- discharge tube; 3- generator λ = 0.8 cm; 4- ISP-51 spectrograph with photoelectric pyrometer photo attachment; 5, 6- detectors with λ = 3 cm and λ = 0.8 cm, respectively.

It was found previously that, with a sufficiently strong electrical field ($E > E_{cr}$), powerful electrostatic instability is excited in a highly ionized hydrogen plasma. This leads to epithermal microwave emission in a wide frequency range ($\omega_{0i} \leq \omega \leq \omega_{0e}$) [3], to an anomalously low plasma conductivity [4], and also to effective heating of electrons [5] and ions [6]. Our experiments were carried out on equipment which is illustrated in Figure 1. The plasma was produced in a cylindrical alundum discharge chamber with an internal diameter of 100 mm. A battery of condensors with a capacity of 15 μF and a discharge voltage up to /204 30 kV was located on aluminum electrodes with a diameter of 80 mm. The maximum current in the discharge reached 200 kA, and its period was 9 μsec. To stabilize the plasma filament, a quasistationary (τ = 5 msec) magnetic field was applied with a strength of up to 20 kOe. The discharge chamber was heated, providing an initial

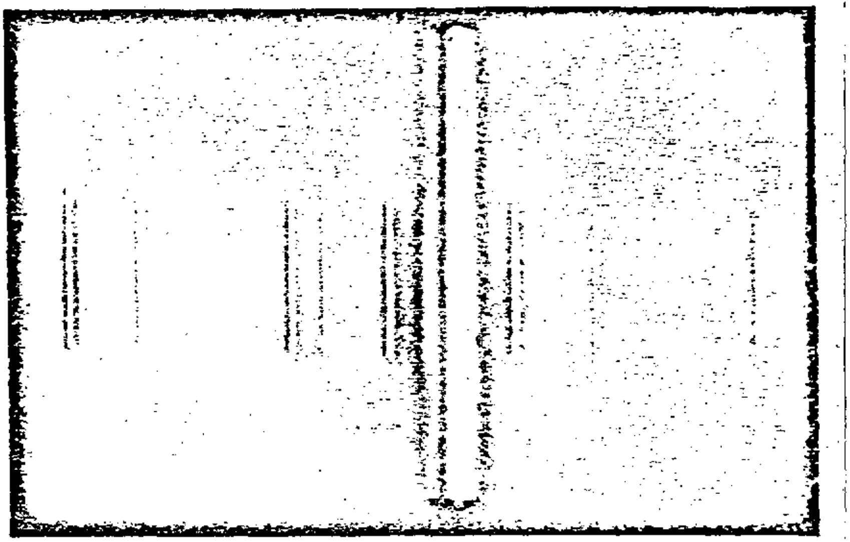

Figure 2. Spectrum of discharge emission close to the HeI 4471.48 Å, ($p = 5 \cdot 10^{-1}$ torr; U_b = 10 kV; H = 3 kOe) line.

vacuum of $1 \cdot 10^{-7}$ torr in the system. The experiments were carried out in helium in a pressure range of $5 \cdot 10^{-1}$ — 10^{-3} torr.

The plasma emission spectrum was photographed through the aperture in the electrode in the direction of the discharge axis by means of a spectrograph with a dispersion of 8 Å/mm. At a pressure of $5 \cdot 10^{-1}$ torr, satellites close to the HeI line were detected:

$$\lambda = 4026{,}19\text{Å}\ (2p^3P^\circ - 5d^3D), \qquad \lambda = 4471{,}48\text{Å}\ (2p^3P^\circ - 4d^3D);$$
$$\lambda = 4921{,}93\text{Å}\ (2p^1P^\circ - 4d^1D)$$

Figure 2 shows one of the satellites close to the forbidden line 4471.48 Å obtained in ten discharges. All of the satellites observed belong to transitions with $\Delta l = 2$ (nP → mF). The determination of the satellite shift close to the lines λ = 4471.48 Å and λ = 4921.93 Å from the forbidden lines (a shift of the forbidden lines was avoided by photographing the emission spectrum of the low pressure glow tube by means of a Fabry-Perot

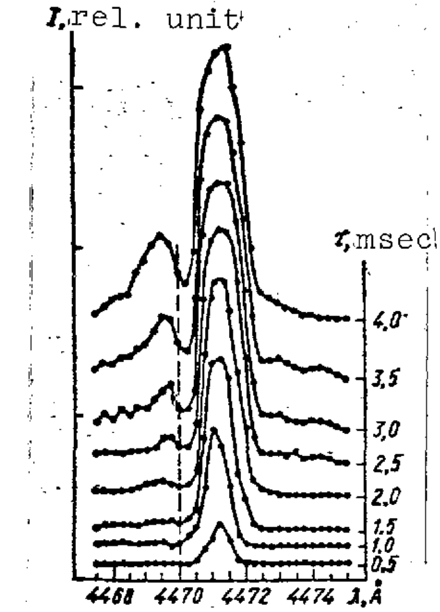

Figure 3. Time change in the discharge emission spectrum close to the line HeI 4471.48 Å ($p = 5 \cdot 10^{-1}$ torr, U_b = 10 kV; H = 3 kOe). The dashed line indicates the position of the forbidden line.

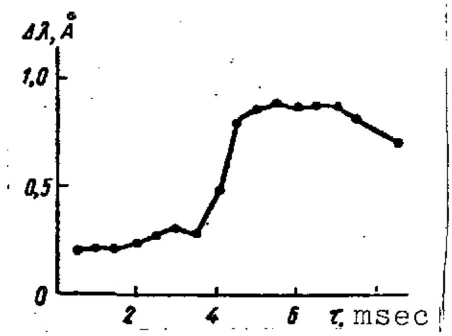

Figure 4. Shift of the "far" satellite during the discharge current period.

interferometer) showed that there were "far" satellites which were displaced from the forbidden lines by 0.3 — 0.7 Å. The intensity of the satellites was $5 \cdot 10^{-2}$ — 10^{-1} of the intensity of the forbidden lines. /205

Photoelectric scanning of the spectrum regions close to these lines was also performed by means of a monochromator with a dispersion of 25 Å/mm. Figure 3 shows the result of one of these measurements of the spectrum region close to the HeI 4471.48 Å line at a pressure of $5 \cdot 10^{-1}$ torr. During the first half period of the discharge current, there was a displacement of the "far" satellite with respect to the forbidden line during the first period of the discharge current (Figure 4). If this displacement is interpreted as being due to electron Langmuir pulsations, then these displacements of the satellites produce concentration changes with time during the first half period from $1 \cdot 10^{13}$ to $2 \cdot 10^{14}$ cm^{-3}. For purposes of comparison, the density of the plasma in the discharge was determined from the Stark widening of the H_β line (averaged over time), which produced a

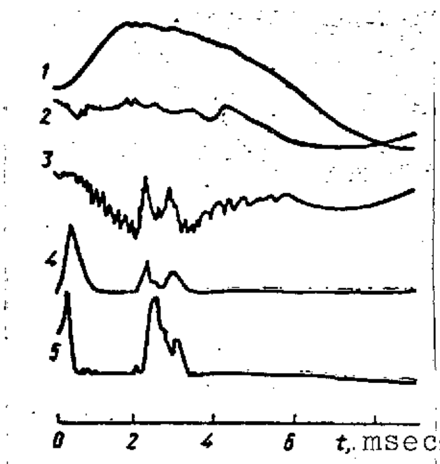

Figure 5. Oscillograms illustrating the behavior of the plasma parameters in time.

1- discharge current; 2- voltage at the electrodes; 3- plasma emission intensity close to the line HeI 4471.48 Å; 4- signal from the detector λ = 3 cm; 5- signal from the detector λ = 0.8 cm with instantaneous probing of the plasma at the same frequency ($p = 2 \cdot 10^{-2}$ torr; U_b = 15 kV; H = 3 kOe).

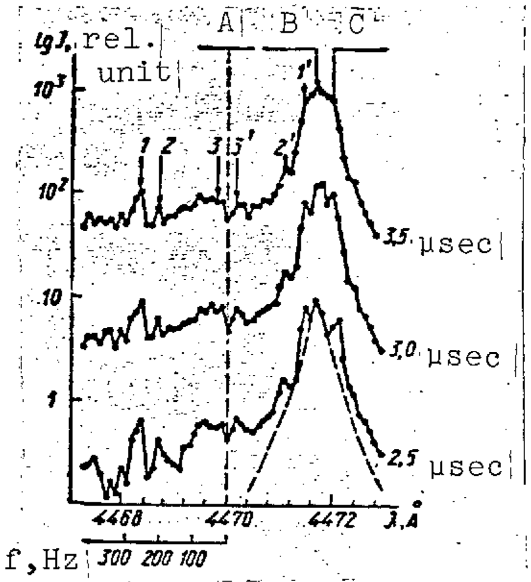

Figure 6. Change in the discharge emission spectrum with time close to the line HeI 4471.48 Å ($p = 2 \cdot 10^{-2}$ torr; U_b = 15 kV; H = 3 kOe); A- forbidden line; B- HeI 4471.48 Å; C- HeI 4471.68 Å.

value of 10^{14} cm^{-3}. Thus, the satellites observed in this case arise in a weakly ionized plasma and are identical to those observed in [2].

It was of interest to study the plasma emission spectrum under conditions when a high frequency instability developed in it, leading to the phenomena described in [3 — 6]. Figure 5 gives oscillograms of the plasma parameters measured at a helium pressure of $2 \cdot 10^{-2}$ torr. One distinguishing feature of this regime was the occurrence of epithermal microwave emission. Along with the occurrence of microwave emission, there was a sharp decrease in the intensity of the line emission, which confirmed the effect observed previously of rapid heating of the electron /206 component [5]. Figure 6 gives the results of scanning the spectral region close to the HeI 4471.48 Å line under these conditions; the results were obtained by averaging the data from ten oscillograms. It may be seen that, close to the forbidden line, there is emission occupying a very wide spectrum with several characteristic symmetrical maxima (1, 1', 2, 2', 3, 3') and a dip close to the location of the forbidden line HeI 4470.03 Å ($2p^{3}P^{0}$ — $4f^{3}F$). It may be assumed that the observed pairs of "satellites" correspond to characteristic plasma frequencies. If the fact is taken into account that, under these conditions the plasma is almost completely ionized, and the plasma density is about $5 \cdot 10^{14}$ cm^{-3}, then the position of the satellites 1, 1' with respect to the forbidden line corresponds to the plasma electron frequency $\Delta\omega_{1.1'} = \omega_{0e}$. The frequency of near "satellites" 3, 3' is about 0.2 ω_{0e}; the frequency of "satellites" 2, 2' equals approximately 0.8 ω_{0e} ($\Delta\omega_2 \approx \Delta\omega_1 - \Delta\omega_3$). Using the expression obtained in the study by Baranger and Mozer for the total satellite intensity with respect to the intensity of the forbidden line,

$$S_{\pm} = \frac{\hbar^2 \langle E_p^2 \rangle R_{ee'}}{6m^2e^2(\Delta \pm \Omega)^2},$$

where $\langle E_p^2 \rangle$ is the mean square of the plasma electric field; $R_{ee'}$ — dimensionless radial integral; m, e — mass and charge of the electron; Δ — distance between the allowed and forbidden lines /207 (in units of angular frequency); Ω — electron plasma frequency, we can determine the strength of the fields of the plasma pulsations. Thus, for the cases shown in Figure 3, this strength is 2 — 6 kV/cm.

Theory makes it possible to determine the level of turbulent plasma pulsations connected with different branches of instabilities of plasma electron pulsations. Thus, in the case of instability in the plasma-beam system, quasilinear theory [7] predicts the occurrence of electron pulsations at frequencies on the order of ω_{0e}, whose level may be determined from the relationship

$$W_{tur} = \frac{\tilde{E}^2}{8\pi} \simeq n' \left(\frac{mU^2}{2}\right)\left(\frac{n'}{n_0}\right)^{1/3},$$

where n_0, n' is the density of the plasma and the beam, respectively; U — velocity of beam electrons. Assuming that

$$\frac{n'}{n_0} \approx 10^{-3}, \frac{mU^2}{2} \approx 10^4 \text{ eV},$$

we obtain $\tilde{E} \approx 10^4$ V/cm.

In a current-carrying plasma, excitation of electron pulsations is also possible due to ion-sound instability or Buneman-Budker instability. The level of turbulent pulsations, /209
related to the ion-sound instability, may be determined [8] as

$$\frac{W_{tur}}{nT} \simeq 2\frac{m_e}{M_i}.$$

The strength of the fields, which follows from this expression, is about $3 \cdot 10^3$ V/cm (at $T_e \simeq 100$ eV).

In the case of Buneman-Budker instability [9],

$$\frac{W_{tur}}{nT} \approx \frac{1}{2\pi}\left(\frac{m_e}{M_i}\right)^{1/3}$$

the field strength is about 10^4 V/cm.

These qualitative determinations show that the level of turbulent pulsations in a plasma, measured from the satellite intensity, do not contradict the predictions of existing theories.

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